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REVIEW AND SYNTHESIS OF BIOASSESSMENT METHODOLOGIES FOR FRESHWATER CONTAMINATED SEDIMENTS

by

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This report presents the results of a review of various bioassessment methods for evaluating the biological effects of in-place contaminated sediments. Promising methodologies are identified with a particular emphasis on those tests which have been developed to the point where incorporation into regulatory programs is feasible. A generic tiered-testing protocol to guide the conduct of these tests is presented.

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PREFACE

Section 118(c)(3) of The Water Quality Act of 1987 authorized the US Environmental Protection Agency's (EPA) Great Lakes National Program Office (GLNPO) to coordinate and conduct a 5-year study and demonstration project relating to the control and removal of toxic substances in the Great Lakes with emphasis on removal of contaminants associated with in-place bottom sediments. This project is called the Assessment and Remediation of Contaminated Sediments (ARCS) program.

Because the US Army Corps of Engineers has expertise in dredging and management of contaminated sediments, the Corps was asked to be involved in the ARCS program. Participation was formalized at the national level via a memorandum agreement between the Assistant Secretary of the Army for Civil Works and the EPA Assistant Administrator for Water (28 Jan 1989) and at the local level via an interagency agreement between the US Army Engineer (USAE) Division, North Central (NCD) and GLNPO (22 Sep 1988). The USAE Waterways Experiment Station (WES) provided technical guidance to NCD.

This report represents the first published technical guidance from WES to NCD as part of the ARCS program. It is a review and compilation of methods used to determine the potential adverse impact of contaminated bottom sediments on aquatic biota. This information was designed to provide initial guidance for developing methods to assess the biological effects of in-place contaminated sediments.

The review was carried out at the Environmental Laboratory (EL) of WES, Vicksburg, MS, from November 1988 to March 1989 by Dr. Tom M. Dillon and Ms. Alfreda B. Gibson of the Ecosystem Research and Simulation Division (ERSD), EL. The work was performed under the general supervision of Dr. Lloyd H. Saunders, Group Leader, Contaminant Mobility and Regulatory Criteria Group. The Chief of ERSD was Mr. Donald Robey and Chief of EL was Dr. John Harrison.

COL Larry B. Fulton, EN, was Commander and Director of WES. Technical Director was Dr. Robert W. Whalin.

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REVIEW AND SYNTHESIS OF BIOASSESSMENT METHODOLOGIES FOR FRESHWATER CONTAMINATED SEDIMENTS

PART I: INTRODUCTION

Background

1. Section 118(c)(3) of The Water Quality Act of 1987 directs the Great Lakes National Program Office (GLNPO) of the US Environmental Protection Agency (USEPA) to conduct a study of techniques for the evaluation, control, and removal of contaminated bottom sediments. Field demonstrations of these techniques will be conducted at the five priority Great Lakes Areas of Concern (AOC); Ashtabula River, Ohio, Buffalo River, New York, Grand Calumet River, Indiana, Saginaw Bay, Michigan, and Sheboygan Harbor, Wisconsin.

2. A necessary first step in this process is the identification of methods for assessing the potential biological impact of in-place contaminated bottom sediments. A number of evaluation procedures have been proposed and/or developed by industry, academia, and state and Federal governments. These techniques vary greatly depending on the stage of development, level of biological organization, logistical requirements, and ability to interpret pertinent ecology. Prudent use of Section 118 program resources suggests that well-developed, proven techniques should be considered in designing and implementing a program.

Objectives

3. This report is a review and synthesis of bioassessment techniques that have been used by others for evaluating the potential biological impacts of contaminated bottom sediments. Promising methodologies are identified and a generic tiered-testing protocol is developed.

PART II: APPROACH

Levels of Biological Organization

4. Bioassessment of contaminated sediment can be carried out at several different levels of biological organization. In order of increasing complexity they are: molecular, cellular, tissue, organismic (whole animal), population, and community. When a perturbation occurs at any level of biological organization, mechanistic explanations can generally be found at lower levels of complexity while ecological implications are usually found at higher levels of complexity (Bayne 1985). In the aquatic environment, the main focus of environmental protection is the maintenance of healthy, viable populations of organisms. Unfortunately, forecasting potential impacts at this level of biological complexity is difficult and predictive capabilities are not well-developed. Bioassessments at lower levels of complexity (molecular-tissue) are usually more sensitive but their ecological relevance is often unclear. For these reasons, a surrogate toxicological approach utilizing organismic end points is often employed (Chapman 1983; Capuzzo, Moore, and Widdows 1988). This approach represents a propitious balance between response sensitivity in the measurement and ecological relevance in data interpretation (Figure 1). It is also logistically attractive since most contract and research facilities in the United States are capable of conducting these types of whole-animal bioassessments. Therefore, to meet the goals of the Section 118(3)(c) program, this review has focused on papers in the literature that utilize the surrogate toxicological bioassessment approach for evaluating in-place contaminated sediments.

Literature Search

5. A broad sweep of the published literature was initiated by using a range of geographic, biological, and physico-chemical search terms with several on-line search services such as Bibliographic Retrieval Services (BRS), DIALOG, SCISEARCH, National Library of Medicine (NLM), ORBIT, and QUESTEL. Coverage included peer-reviewed journals such as Great Lakes Research as well as the "gray literature" (e.g., National Technical Information Service). This initial search yielded nearly 500 potentially useful citations. After careful

LEVELS OF BIOLOGICAL ORGANIZATION

	BIOCHEMICAL	ORGANISMIC	POPULATIONS	COMMUNITIES
TYPICAL RESPONSE PARAMETERS	BLOOD CONSTITUENTS PROXIMATE COMPOSITION ADENYLATE POOLS NUCLEIC ACIDS MEMBRANES ENZYMES	BEHAVIOR MORPHOLOGY OSMOREGULATION METABOLISM GROWTH REPRODUCTION	ENERGY FLOW NUTRIENT CYCLING INTRASPECIFIC INTERACTIONS ABUNDANCE	ENERGY FLOW NUTRIENT CYCLING INTRASPECIFIC INTERACTIONS ABUNDANCE DIVERSITY
RESPONSE TIME	MINUTES TO HOURS	HOURS TO DAYS	WEEKS TO YEARS	MONTHS TO DECADES

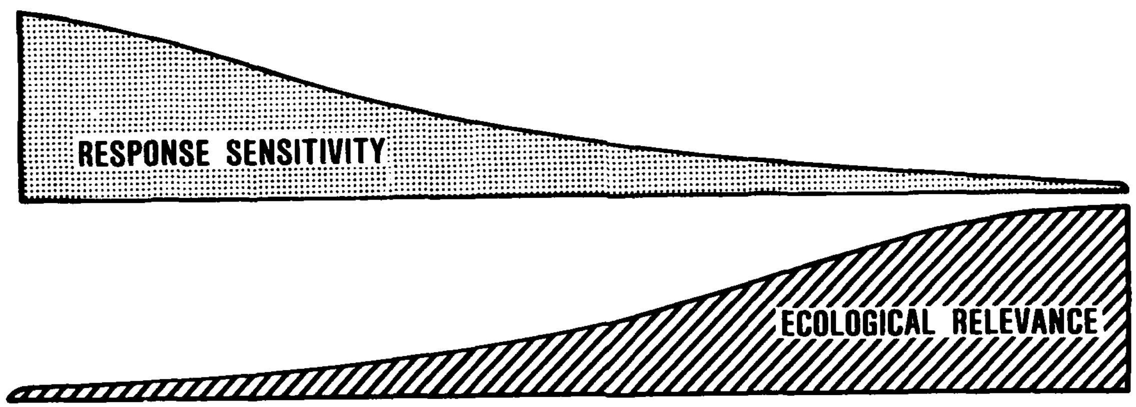

Figure 1. Levels of biological organization

inspection, approximately 200 were deemed applicable for this review. Citations not already on file were obtained and entered into onsite user files. Publications were then individually reviewed for content and technical quality.

6. Scientists and active researchers in the field of sediment bioassessment often participate in workshops and seminars. Literature resulting from these activities can be a very valuable source of information since it often reflects "the best of the best" from the scientific community. Much of this literature also contains any technical consensus agreements arrived at by experts in the field. Therefore, as part of this literature search, current activities in the following areas were reviewed:

a. American Society for Testing and Materials

b. International Joint Commission

c. US Environmental Protection Agency

d. US Army Corps of Engineers

7. This literature review was restricted to activities and publications dealing with the freshwater environment only. It is acknowledged that some information from the marine and estuarine literature may be conceptually applicable to the generic subject of bioassessment. However, the practical aspect of combining that information with the freshwater literature (e.g., species selection) and formulating specific recommendations for GLNPO precludes its inclusion.

PART III: RESULTS AND DISCUSSION

Bioaccumulation Potential

8. The bioassessment process consists of two elements; (a) the determination of bioaccumulation potential, and (b) an evaluation of biological effects. The majority of literature reviewed for this report emphasizes the bioaccumulation of contaminants from sediment (compiled in Appendix A). The biological effects of freshwater sediment were examined in a smaller number of papers. This dominance of bioaccumulation studies has been noted in previous reviews (Leland, Copenhaver, and Wilkes 1975; DePinto, Young, and Martin 1983; Olsen 1984; Lathrop and Davis 1986; Davis, Denbow, and Lathrop 1987; Davis and Denbow 1988).

9. A determination of contaminant bioavailability is an important and requisite first step in the bioassessment process because from a toxicological perspective, "there are no toxic substances, only toxic doses" [Paracelsus ca. 1540]. In other words, before contaminated sediments can have an effect, the organism must experience a dose. Most environmental contaminants are associated very closely with the sediment matrix and not readily available for uptake (Neff 1984). This is especially true for some of the more toxic nonpolar compounds that are very hydrophobic. McFarland and Clarke (1987) have developed a two-tiered process for determining the bioaccumulation potential of these neutral organic contaminants. The first tier estimates the equilibrium tissue concentration relative to the sediment using fugacity theory, data from sediment chemistry, and representative lipid concentrations in biota. If this screening exercise indicates bioaccumulation beyond levels of concern, empirical determinations of bioaccumulation potential may be carried out in the second tier. Time-sequenced samples are taken during laboratory experiments to estimate steady-state tissue concentrations. Long-term exposures may also be carried out to verify predictions of steady-state concentrations.

Contaminant-Specific Biological Effects

10. Papers that did report the biological effects of freshwater sediments focused primarily on a specific contaminant or class of

contaminants. These investigations employed either a spiking procedure or attempted to correlate concentrations of sediment contaminants with observed biological effects. The sediment spiking approach allows one to evaluate the fate and effects of individual contaminants in the sediment matrix under controlled conditions (for representative examples see Muir, Townsend, and Lockhart (1983); Cairns et al. (1984); Adams, Kimerle, and Mosher (1985); Adams et al. (1986); Nebeker et al. (1986); Swindoll and Applehans (1987); Wood et al. (1987); Hammer, Merkowsky, and Huang (1988); Schuytema et al. (1988). Care must be taken, however, when interpreting the results of sediment spiking experiments especially if one is attempting to simulate natural conditions.

11. Bioaccumulation from spiked sediments can usually be resolved into two phases; a rapid phase lasting hours to days and a slow phase lasting weeks to months (Muir et al. 1983, Wood et al. 1987). This pattern closely mirrors reported desorption curves for a variety of contaminants (Karickhoff 1980; Nyffeler, Li, and Santschi 1984; Tessier et al. 1984; Karickhoff and Morris 1985). Observations on biological effects made during the initial desorption/bioaccumulation phase would not approximate chronic exposure conditions with natural sediments. Complicating the issue is the fact that spiking methods vary greatly and post-spike equilibration times range from a few hours (Hall et al. 1986) to several weeks (Oliver 1987).

12. The other chemical-specific publications dealing with biological effects relate sediment toxicity to concentrations of individual contaminants in sediment. Attempts to identify these correlations have experienced varying degrees of success (Wentsel, McIntosh, and Atchison 1977; Laskowski-Hoke and Prater 1981; West et al. 1986; Fabacher et al. 1988). Generating significant correlations, however, does not mean a causal relationship has been identified. Natural sediments typically contain a wide variety of contaminants; some known, some unknown, and some extremely difficult to detect analytically. This is especially true for sediments from the Great Lakes AOC's, many of which are located in highly industrialized waterways. Sediments from these locations contain hundreds of anthropogenic substances.

13. Projecting cause-and-effect relationships based on an inventory of sediment chemistry ignores several important phenomena:

a. Contaminant-contaminant interactions (e.g., synergism)

b. Variations in contaminant activity (e.g., bioavailability)

c. Chemically undetected toxic substances

The furan and dioxin congeners, especially 2,3,7,8-TCDD, are very good examples of the latter possibility. These compounds are extremely toxic, difficult to analyze, and found at very low concentrations in environmental samples.

Generic Bioassessment Techniques for Freshwater Sediments

14. One way to avoid some of the problems associated with the chemical-by-chemical approach is to consider the contaminated sediment as a single entity. In other words, assess the aggregate effect of all its constituents. Survival in acute or short-term sediment exposures is the most common means of measuring this aggregate effect. The opposite of survival, mortality, represents a clear, albeit severe, potential for adverse environmental impact. The interpretation of acute toxicity bioassays is straightforward. Results are binary; the test animals either survived or they did not.

15. In addition to survival, chronic or sublethal effects on aquatic animals exposed to contaminated sediment have been evaluated, although much less frequently. There are several reasons why chronic or sublethal effects are of interest. As discussed earlier, many environmental contaminants are tightly bound to the sediment matrix and bioaccumulation may occur very slowly. Some compounds may not be acutely toxic but rather exert subtle sublethal effects only after prolonged or chronic exposure. Since the ultimate goal in protecting any biological resource is the maintenance of viable populations, growth and reproduction are two of the more desirable chronic or sublethal end points (Bayne et al. 1980).

16. Investigations were identified in this literature review that have used survival, growth, and reproduction to evaluate freshwater sediment regardless of its contaminant composition. These references have been grouped below according to individual test species. Descriptive comments germane to each test are also provided.

Bioassay Test Organisms for Evaluating Freshwater Sediment

Daphnia magna (cladoceran)

Availability:

Culture or field-collected

Bioaccumulation Potential:

Generally feasible only for single compounds

Biological Effects:

Acute lethality (24-96 hr)

Survival, growth, and reproduction in full or partial life cycle exposures

For detailed methods see: Prater and Anderson (1977), Hoke and Prater (1980), Malueg et al. (1983, 1984), Nebeker et al. (1984), LeBlanc and Surprenant (1985), Ziegenfuss and Adams (1985), Adams et al. (1986)

Comments: More sensitive than most other test species. Primarily nektonic and perhaps epibenthic. Not intimately associated with the benthic environment.

Chironomus tentans (midge)

Availability:

Culture or field-collected

Bioaccumulation Potential:

Generally feasible only for single compounds

Biological Effects:

Acute lethality (24-96 hr)

Survival and growth in partial life cycle exposures

Adult emergence

Behavioral avoidance

For detailed methods see: Mosher and Adams (1982); Mosher, Kimerle, and Adams (1982); Nebeker et al. (1984); Ziegenfuss and Adams (1985); Wentsel et al. (1977); Wentsel, McIntosh, and Atchison (1977); Wentsel, McIntosh, and McCafferty (1978); Adams et al. (1986)

Comments: Larval growth occurs in four instars, each lasting approximately one week. First instars typically show poor survival in the laboratory so all tests are initiated with second-instar larvae. Survival and growth are measured after reaching the fourth instar. Normal adult emergence is usually very low; less than 60 percent. *C. riparius* has also been suggested due to its larger size and slightly faster developmental time. It is also more common in the Great Lakes than *C. tentans*. However, methods for this congener are not as well-developed.

Hexagenia limbata (mayfly)

Availability:

Field-collected

Bioaccumulation Potential:

Generally feasible only for single compounds

Biological Effects:

Acute lethality (24-96 hr)

Growth

Adult emergence

For detailed methods see: Prater and Anderson (1977), Hoke and Prater (1980), Landrum et al. (1983), Malueg et al. (1983, 1984), Nebeker et al. (1984), Landrum and Poore (1988)

Comments: Long generation times and variable growth rates make laboratory cultures difficult. Cannibalism and high control mortality observed in larger animals.

Asellus communis (isopod)

Availability:

Field-collected

Bioaccumulation Potential:

Useful with natural sediments

Biological Effects:

Acute lethality (24-96 hr)

For detailed methods see: Prater and Anderson (1977), Lewis and McIntosh (1986)

Comments: Paucity of background information and no culturing techniques.

Hyalella azteca (amphipod)

Availability:

Culture or field-collected

Bioaccumulation Potential:

Generally feasible only for single compounds

Biological Effects:

Acute lethality (24-96 hr)

Survival and growth in partial life cycle exposures

For detailed methods see: Landrum and Scavia (1983), Nebeker et al. (1984), Nebeker and Miller (1988)

Comments: The life cycle is approximately 27 days. Easy to culture but determination of reproductive success is difficult due to non-quantitative recovery of young amphipods while sieving sediment.

Gammarus lacustris (amphipod)

Availability:

Culture or field-collected

Bioaccumulation Potential:

Useful with natural sediments

Biological Effects:

Acute lethality (24-96 hr)

For detailed methods see: Nebeker et al. (1984)

Comments: Cannibalism and high control mortality observed in larger animals.

Pontoporeia hoyi (amphipod)

Availability:

Field-collected

Bioaccumulation Potential:

Generally feasible only for single compounds

Biological Effects:

Acute lethality (24-96 hr)

For detailed methods see: Gannon and Beeton (1971), Landrum et al. (1983), Landrum (1988)

Comments: Indigenous to the Great Lakes and an important component of the benthic ecosystem. Difficult to collect and must be maintained under cold-water conditions.

Stylodrilus heringianus (oligochaete)

Availability:

Field-collected

Bioaccumulation Potential:

Generally feasible only for single compounds

Biological Effects:

Acute lethality (24-96 hr)

Burrowing activity

For detailed methods see: Keilty, White, and Landrum (1988), White and Keilty (1988)

Comments: Indigenous to the Great Lakes and an important component of the benthic ecosystem. Not believed to be very sensitive to environmental contaminants.

Pimephales promelas (fathead minnow)

Availability:

Culture or field-collected

Bioaccumulation Potential:

Useful with natural sediments

Biological Effects:

Acute lethality (24-96 hr)

Survival, growth, and reproduction in full or partial life cycle exposures

For detailed methods see: Mac et al. (1984), Dillon (1988), Hoke and Prater (1980), LeBlanc and Surprenant (1985), Prater and Anderson (1977)

Comments: Large size and high lipid content facilitate bioaccumulation studies.

Institutional Bioassessment Techniques For Freshwater Sediments

17. As discussed in the Introduction, many institutional programs have adopted the surrogate toxicological approach for evaluating freshwater sediments. This approach, which extrapolates from laboratory observations with whole animals to potential impacts on feral populations in the field, emphasizes effects on survival, growth, and reproduction. It has the added benefit of being understood by the general public. This facilitates communication of technical findings to a nontechnical audience, a responsibility shared by many institutional programs.

18. In the course of this review, it became apparent that some institutional programs with divergent mission responsibilities utilize very similar bioassessment techniques for freshwater sediment. It is therefore reasonable to conclude that similarities found across such diverse groups probably represent a sound technical consensus of the scientific community. Activities in the following groups were reviewed.

a. American Society for Testing and Materials

b. International Joint Commission

c. US Environmental Protection Agency

d. US Army Corps of Engineers

American Society for Testing and Materials (ASTM)

19. The primary goal of ASTM is to foster the development of technically sound standard methods and materials. The Sediment Toxicology Subcommittee (E47.03) is one of the newest work groups in ASTM. With 225 members, it is also the largest subcommittee in ASTM. This size indicates a widespread interest in the development of standardized sediment-testing methods. This subcommittee is chaired by Dr. Chris G. Ingersoll of the US Fish and Wildlife Service (USFWS) in Columbia, MO.

20. Separate task groups were formed in the Sediment Toxicity Subcommittee to address four issues;

a. Sediment collection, storage, characterization, and manipulation

b. Experimental designs for sediment bioassays

c. Solid phase sediment bioassays to assess toxicity

d. Solid phase sediment bioassays to assess bioaccumulation potential

21. A draft guidance document for conducting solid phase toxicity tests with freshwater sediments has been submitted to the Subcommittee for discussion and balloting (Nelson, Ingersoll, and Dwyer, in preparation). This is a generic "how-to" document with a discussion on topics such as statistical and experimental design, necessary equipment, potential non-treatment effects, and safety considerations. The authors recommend three test species; *Hyalella azteca, Chironomus tentans, and Chironomus riparius*. Detailed materials and methods specific to each organism are provided in three separate appendixes. Brief summaries of test conditions for each species are given below.

a. *Hyalella azteca.* Provide exposure at 20° C in 1-ℓ beakers or 20-ℓ aquaria for <10 days (short-term partial life cycle) or >10 days (long-term partial life cycle). Monitor survival and growth. Reproduction can be evaluated if test duration exceeds 30 days.

b. *Chironomus tentans.* Provide exposure at 20° to 23° C in 2-ℓ or 20-ℓ aquaria for 10-14 days when measuring larval survival and growth and 25 days when measuring adult emergence. Exposures can also be carried out in 50-mℓ centrifuge tubes under some experimental designs.

c. *Chironomus riparius.* Conditions are generally similar to those for *Chironomus tentans* although test development for this species is not as well developed. The advantages of *C. riparius* are its larger size and slightly faster development time. It is also more common in the Great Lakes than *C. tentans*.

22. ASTM guidance on how to assess bioaccumulation potential of contaminants in freshwater sediments is in its formative state. Discussion outlines indicate that at least one of the recommended test organisms will be the fathead minnow, *Pimephales promelas*.

23. Three different phases of sediment can be evaluated; solid phase, suspended particulate phase, and elutriate. The decision on which phase to test is dependent on the part of the environment in which potential impacts may occur. The selection of which phase to test can also be driven by a specific research hypothesis. Most of the Sediment Subcommittee's concerns have focused on the solid-phase testing of sediments. Laboratory research and field observations indicate that if significant impacts from contaminated sediments do occur, they are usually associated with the benthic environment (Engler 1980). In addition to ASTM, the USFWS, USEPA, and the US Army Corps of Engineers have recommended that primary emphasis be placed on solid phase testing unless there is some reason to believe impacts in the water column may occur (Saucier et al. 1978; Mac et al. 1984; Seelye, Hesselberg, and Mac 1982; Seelye and Mac 1984).

International Joint Commission (IJC)

24. The IJC is a long-standing bilateral commission composed of representatives from Canada and the United States. The United States and Canada share many common waterways located primarily in and around the Great Lakes. One of the common areas of interest is the pollution of these waterways and specifically the presence of environmental contaminants in bottom sediments. The Sediment Subcommittee of the IJC was formed to address this issue. It has recently reviewed a variety of procedures for the bioassessment of contaminated sediments in the Great Lakes (IJC 1988). The report recommends a tiered approach that includes the following six laboratory bioassessment techniques.

a. Microtox. In this assay, luminescent bacteria (*Photobacterium phosphoreum*) are exposed for a short period of time (15-30 min is typical) to an extract or aqueous sample. A decrease in luminescence is interpreted as a sign of toxicity. The primary advantage of this assay is its quickness and low cost per sample. The report notes, however, that this bacterial assay is less sensitive to mercury and cadmium than *Daphnia magna* and that it may be insensitive to chlorinated hydrocarbons such as polychlorinated biphenyls (PCB's). The Microtox assay may be useful in screening large numbers of samples when broad overall assessments regarding groups of samples are being made. It may be less useful than more traditional and reliable screening bioassays (e.g., *Daphnia magna*) when decisions regarding individual samples are needed.

b. Algal photosynthesis. Photosynthesis is the autotrophic synthesis of organic material by plants using light as an energy source. The fixation of ^{14}C by algae is utilized in this assay as a surrogate for photosynthesis. Either laboratory cultures of algae (e.g., *Selenastrum capricornutum*) or field-collected samples are tested. This assay is used to evaluate potential water column impacts. Fisheries and Oceans Canada utilizes the algal photosynthesis assay extensively.

c. Life cycle bioassays with *Daphnia magna*. See earlier discussions regarding this organism.

d. Chronic benthic invertebrate bioassays. Three test species are recommended: *Chironomus tentans*, *Hyalella azteca*, and *Hexagenia limbata*. See earlier discussions regarding these organisms.

e. Bioaccumulation with *Pimephales promelas*. See earlier discussions regarding this organism.

f. Ames test. Fish from areas containing contaminated freshwater sediment (especially polycyclic aromatic hydrocarbons) have been observed with various internal tumors and epidermal papillomas. Neoplasia has been experimentally induced in freshwater fish exposed to contaminated sediment in the laboratory. The somatic mutation theory requires the mutation of genetic material prior to carcinogenesis. Therefore, an assay that identifies mutagenic activity would indicate a potential for carcinogenicity. The Ames test, developed for mammalian toxicology, is the most commonly used assay for mutagenicity. Specific strains of *Salmonella* are exposed to sediment extracts and the number of revertants (mutagenicity) is observed. Microsomal fractions from rat liver or fish liver can be added to these extracts to detect mutagens that require activation. In mammals, the induction of cancer correlates strongly and positively with results of the Ames test. However, it has been criticized for showing no response in many instances where subsequent tumors were detected (Tennant 1987).

25. The IJC report acknowledges that much research and development is required in the area of genotoxicity. It proposes two approaches. In one, a chemical-by-chemical determination of mutagenicity would be carried out with selected contaminants. Results would then be compared to bulk sediment concentrations. The other approach is more direct. Using the small fish carcinogensis model (Hawkins, Overstreet, and Walker 1988), in vivo fish bioassays would be carried out with the test sediment. Fish would be monitored over time for the presence or absence of neoplasia.

26. The current literature review discovered additional citations not contained in the IJC report in which the Ames test is used to evaluate the mutagenicity of freshwater sediments (Allen, Noll, and Nelson 1983; Samoiloff et al. 1983; West et al. 1986; Oishi and Takahashi 1987). Two recent reports suggest another genotoxic end point (unscheduled DNA synthesis) may also be useful and should receive further attention (Fabacher et al. 1988, West et al. 1988).

US Environmental Protection Agency (USEPA)

27. In April 1988, Region V USEPA published its draft guidance for sampling and testing of freshwater sediments. This guidance uses bulk chemistry data to classify sediments into three categories; Type I (probably unpolluted), Type III (probably polluted), and Type II (other). Most of the document is devoted to describing this classification scheme and to sediment sampling procedures. Three bioassessment protocols recommended by Region V in this document are shown below. See earlier discussions regarding details of organism-specific procedures.

- a. Elutriate bioassays with cladocerans. *Daphnia magna* is recommended.
- b. Solid phase sublethal sediment bioassays with either the midge, *Chironomus tentans*, or the amphipod, *Hyalella azteca*.
- c. Solid phase bioaccumulation studies with the fathead minnow, *Pimephales promelas*.

US Army Corps of Engineers (USACE)

28. In 1985, the US Army Engineer District, St. Paul, cosponsored a workshop with the Wisconsin Department of Natural Resources (DNR) for the purpose of identifying bioassessment methods for the regulatory evaluation of freshwater sediment. Detailed proceedings of this workshop and supporting technical documentation can be found in Dillon and Gibson (1986). Major consensus agreements reached by the workshop's participants are summarized below.

- a. Tiered or hierarchical testing represents a technically sound process for evaluating freshwater sediments.
- b. Inventories of chemicals in sediment give no indication of biological effects but are useful in deciding if further evaluation is necessary. Chemical inventories can be used to predict bioaccumulation potential of certain contaminants under certain conditions.
- c. Solid phase sediment testing should be emphasized unless there is a reason to believe water column impacts may occur.

d. Growth and reproduction should be considered the highest priority sublethal end points.

e. Some sort of oncological assessment is highly desirable. However, no single method could be recommended as having been sufficiently developed for use in a regulatory program.

29. The generic tiered-testing protocol produced by the workshop participants has been more fully developed by the St. Paul District. Working in conjunction with the Wisconsin DNR, this protocol has been tested in the laboratory using sediments from the Great Lakes and Mississippi River (Ward, in preparation). The bioassessment techniques contained in this tiered-testing protocol are summarized below.

a. Solid phase acute (48-hr) lethality bioassay with *Daphnia magna*.

b. Solid phase chronic (10-day) bioassay measuring survival, growth, and reproduction in *Daphnia magna*.

c. Solid phase chronic (14-day) bioassay measuring survival and growth in *Chironomus tentans*.

d. Solid phase bioaccumulation (30-day) with fathead minnows, *Pimephales promelas*.

PART IV: SUMMARY AND RECOMMENDATIONS

30. Review of the bioassessment methodologies for freshwater contaminated sediments results in the following conclusions:

- a. The bioassessment literature for freshwater sediment is dominated by investigations that evaluate contaminant bioaccumulation and not the biological effects of contaminated sediments.
- b. The majority of investigations that evaluate biological effects have focused on specific contaminants or groups of contaminants.
- c. The chemical-by-chemical approach utilized in many of these bioassessment techniques cannot account for three important phenomena:
  - (1) Contaminant-contaminant interactions (e.g., synergism).
  - (2) Variations in contaminant activity (e.g., bioavailability).
  - (3) Chemically undetected toxic substances (e.g., dioxin).
- d. Several institutional programs with diverse mission responsibilities (ASTM, IJC, USEPA, USACE) are using or considering very similar bioassessment techniques for the evaluation of contaminated freshwater sediments. These similarities strongly suggest that a technical consensus exists in the scientific community regarding appropriate bioassessment techniques. These similarities can be summarized as follows:
  - (1) Tiered testing represents a logical, technically sound approach for evaluating contaminated sediments.
  - (2) Sensitive test species, especially cladocerans such as *Daphnia magna*, should be used in the initial biological screening tiers.
  - (3) Chronic or sublethal testing should include an evaluation of impacts on growth and reproductive success.
  - (4) Recommended test species for evaluating chronic or sublethal impacts are the midge, *Chironomus tentans*, and the amphipod, *Hyalella azteca*.
  - (5) The fathead minnow, *Pimephales promelas*, may be used to evaluate bioaccumulation potential. However, fish, as well as most aquatic animals, can metabolize polycyclic aromatic hydrocarbons. Therefore, parent compounds may not be easily detected in tissues.
  - (6) Bioassessments should emphasize solid phase sediment bioassays unless there is a reason to believe that water column organisms will be seriously impacted.

31. The following protocol is recommended for tiered-testing bioassessment.

a. Tier I. Initial evaluation of existing data.

b. Tier II. Chemical analysis of sediment.

Bioaccumulation potential: Calculation of equilibrium tissue concentrations of neutral organics relative to sediment concentrations.

Biological effects: Screening bioassays.

c. Tier III. Bioaccumulation potential: Empirical determination during laboratory exposures.

Biological effects: Short-term solid phase toxicity tests.

d. Tier IV. Bioaccumulation potential: Steady-state determination and important factors affecting uptake.

Biological Effects: Chronic or sublethal solid phase tests and important factors affecting toxicity.

REFERENCES

Adams, W. J., Kimerle, R. A., and Mosher, R. G. 1985. "Aquatic Safety Assessment of Chemicals Sorbed to Sediments," Seventh Symposium on Aquatic Toxicology and Hazard Assessment: ASTM STP 854, R. D. Cardwell, R. Purdy, and R. C. Bahner, eds., American Society for Testing and Materials, Philadelphia, PA, pp 429-453.

Adams, W. J., Ziegenfuss, P. S., Renaudette, W. J., and Mosher, R. G. 1986. "Comparison of Laboratory and Field Methods for Testing the Toxicity of Chemicals Sorbed to Sediments," Aquatic Toxicology and Environmental Fate, Vol 9, ASTM STP 921, T. M. Poston and R. Purdy, eds., American Society for Testing and Materials, Philadelphia, PA, pp 493-513.

Allen, H. E., Noll, K. E., and Nelson, R. E. 1983. "Methodology for Assessment of Potential Mutagenicity of Dredged Materials," Environmental Technology Letters, Vol 4, pp 101-106.

Bayne, B. L. 1985. "Cellular and Physiological Measures of Pollution Effects," Marine Pollution Bulletin, Vol 16, pp 127-128.

Bayne, B. L., Anderson, J., Engel, D., Gilfillan, E., Hoss, D., Lloyd, R.,and Thurberg, F. P. 1980. "Physiological Techniques for Measuring the Biological Effects of Pollution in the Sea," Reunion Conseil International por l'Exploration de la Mer, Vol 179, pp 88-90.

Cairns, M. A., Nebeker, A. V., Gakstatter, J. H., and Griffis, W. L. 1984. "Toxicity of Copper-Spiked Sediments to Freshwater Invertebrates," Environmental Toxicology and Chemistry, Vol 3, pp 435-445.

Capuzzo, J. M., Moore, M. N., and Widdows, J. 1988. "Effects of Toxic Chemicals in the Marine Environment: Predictions of Impacts for Laboratory Studies," Aquatic Toxicology, Vol 11, pp 303-311.

Chapman, P. M. 1983. "Do Organisms in Laboratory Tests Respond Like Organisms in Nature?," Sixth Symposium on Aquatic Toxicology and Hazard Assessment, ASTM STP 802, W. E. Bishop, R. D. Cardwell, B. B. Heidolph, eds., American Society for Testing and Materials, Philadelphia, PA, pp 315-327.

Davis, W. S., and Denbow, T. J. 1988. "Aquatic Sediments," Journal of the Water Pollution Control Federation, Vol 60, pp 1077-1088.

Davis, W. S., Denbow, T. J., and Lathrop, J. E. 1987. "Aquatic Sediments," Journal of the Water Pollution Control Federation, Vol 59, pp 586-597.

DePinto, J. V., Young, T. C., and Martin, S. C. 1983. "Aquatic Sediments," Journal of the Water Pollution Control Federation, Vol 55, pp 822-829.

Dillon, T. M. 1988. "Relationship Between PCB Tissue Residues and Reproductive Success of Fathead Minnows," Technical Note EEDP-01-13, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Dillon, T. M., and Gibson, A. B. 1986. "Bioassessment Methodologies for the Regulatory Testing of Freshwater Dredged Material; Proceedings of a Workshop," Miscellaneous Paper EL-86-6, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Engler, R. M. 1980. "Prediction of Pollution Potential Through Geochemical and Biological Procedures: Development of Regulation Guidelines and Criteria for the Discharge of Dredged and Fill Material," Contaminants and Sediments, Vol 1, Robert A. Baker, ed., Ann Arbor Science Publishers, Inc., Ann Arbor, MI, pp 143-169.

Fabacher, D. L., Schmitt, C. J., Besser, J. M., and Mac, M. J. 1988. "Chemical Characterization and Mutagenic Properties of Polycyclic Aromatic Compounds in Sediment from Tributaries of the Great Lakes," Environmental Toxicology and Chemistry, Vol 7, pp 529-543.

Gannon, J. E., and Beeton, A. M. 1971. "Procedures for Determining the Effects of Dredged Sediments on Biota-Benthos Viability and Sediment Selectivity Tests," Journal of the Water Pollution Control Federation, Vol 43, pp 392-398.

Hall, S. W., Dickson, K. L., Saleh, F. Y., and Rogers, J. H., Jr. 1986. "Effects of Suspended Solids on the Bioavailability of Chlordane to *Daphnia magna*," Archives of Environmental Contamination and Toxicology, Vol 15, pp 529-534.

Hammer, U. T., Merkowsky, A. T., and Huang, P. M. 1988. "Effects of Oxygen Concentrations on Release of Mercury from Sediments and Accumulation by *Ceratophyllum demersum* and *Anodonta grandis*," Archives of Environmental Contamination and Toxicology, Vol 17, pp 257-262.

Hawkins, W. E., Overstreet, R. M., and Walker, W. W. 1988. "Carcinogenicity Tests with Small Fish Species," Aquatic Toxicology, Vol 11, pp 113-128.

Hoke, R. A., and Prater, B. L. 1980. "Relationship of Percent Mortality of Four Species of Aquatic Biota from 96-hour Sediment Bioassays of Five Lake Michigan Harbors and Elutriate Chemistry of the Sediments," Bulletin of Environmental Contamination and Toxicology, Vol 25, pp 394-399.

International Joint Commission. 1988. "Procedures for the Assessment of Contaminated Sediment Problems in the Great Lakes," report of the Sediment Subcommittee and its Assessment Work Group to the Water Quality Board.

Karickhoff, S. W. 1980. "Sorption Kinetics of Hydrophobic Pollutants in Natural Sediments," Contaminants and Sediments, Vol II, R. A. Baker, ed., Ann Arbor Science Publishers, Inc., Ann Arbor, MI, pp 193-205.

Karickhoff, S. W., and Morris, K. R. 1985. "Sorption Dynamics of Hydrophobic Pollutants in Sediment Suspensions," Environmental Toxicology and Chemistry, Vol 4, pp 469-474.

Keilty, T. J., White, D. S., and Landrum, P. F. 1988. "Short-Term Lethality and Sediment Avoidance Assays with Endrin-Contaminated Sediment and Two Oligochaetes from Lake Michigan," Archives of Environmental Contamination and Toxicology, Vol 17, pp 95-101.

Landrum, P. F. 1988. "Toxicokinetics of Organic Xenobiotics in the Amphipod (*Pontoporeia hoyi*): Role of Physiological and Environmental Variables," Aquatic Toxicology, Vol 12, pp 245-271.

Landrum, P. F., and Poore, R. 1988. "Toxicokinetics of Selected Xenobiotics in *Hexagenia limbata*," Journal of Great Lakes Resources, Vol 14, pp 427-437.

Landrum, P. F., and Scavia, D. 1983. "Influence of Sediment on Anthracene Uptake, Depuration, and Biotransformation by the Amphipod (*Hyalella azteca*)," Canadian Journal of Fishing and Aquatic Science, Vol 40, pp 298-305.

Landrum, P. F., Eadie, B. J., Faust, W. R., Morehead, N. R., and McCormick, M. J. 1983. "Role of Sediment on the Bioaccumulation of Benzo(a)pyrene by the Amphipod, (*Pontoporeia hoyi*)," Polynuclear Aromatic Hydrocarbons: Eighth International Symposium on Mechanisms, Methods and Metabolism, M. W. Cooke and A. J. Dennis, eds., Battelle Press, Columbus, OH.

Laskowski-Hoke, R. A., and Prater, B. L., 1981. "Relationship of Mortality of Aquatic Biota from 96-hour Sediment Bioassays and the Change in Chemical Composition of the Test Water," Bulletin of Environmental Contamination and Toxicology, Vol 26, pp 323-327.

Lathrop, J. E., and Davis, W. S. 1986. "Aquatic Sediments," Journal of the Water Pollution Control Federation, Vol 58, pp 684-699.

LeBlanc, G. A., and Surprenant, D. C. 1985. "A Method of Assessing the Toxicity of Contaminated Freshwater Sediments," Seventh Symposium on Aquatic Toxicology and Hazard Assessment, ASTM STP 854, R. D. Cardwell, R. Purdy, and R. C. Bahner, eds., American Society for Testing and Materials, Philadelphia, PA, pp 269-283.

Leland, H. V., Copenhaver, E. D., and Wilkes, D. J. 1975. "Heavy Metals and Other Trace Elements," Journal of the Water Pollution Control Federation, Vol 47, pp 1635-1656.

Lewis, T. E., and McIntosh, A. W. 1986. "Uptake of Sediment-Bound Lead and Zinc by the Freshwater Isopod (*Asellus communis*) at Three Different pH Levels," Archives of Environmental Contaminants and Toxicology, Vol 15, pp 495-504.

Mac, M. J., Edsall, C. C., Hesselberg, R. J., and Sayers, R. E., Jr. 1984. "Flow-through Bioassay for Measuring Bioaccumulation of Toxic Substances from Sediment," Report No. 905/3-84-007, Environmental Protection Agency, Ann Arbor, MI.

Malueg, K. W., Schuytema, G. S., Gakstatter, J. H., and Krawczyk, D. F. 1983. "Effect of *Hexagenia* on *Daphnia* Response in Sediment Toxicity Tests," Environmental Toxicology and Chemistry, Vol 2, pp 73-82.

Malueg, K. W., Schuytema, G. S., Krawczyk, D. F., and Gakstatter, J. H. 1984. "Laboratory Sediment Toxicity Tests, Sediment Chemistry and Distribution of Benthic Macroinvertebrates in Sediments from the Keweenaw Waterway, Michigan," Environmental Toxicology and Chemistry, Vol 3, pp 233-242.

McFarland, V., and Clarke, J. 1987. "Simplified Approach for Evaluating Bioavailability of Neutral Organic Chemicals in Sediment," Environmental Effects of Dredging Technical Notes EEDP-01-8, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Mosher, R. G., and Adams, W. J. 1982. "Methods for Conducting Acute Toxicity Tests with the Midge *Chironomus tentans*," Proceedings of a Workshop on Bioassessment Methodologies for the Regulatory Testing of Freshwater Dredged Material, Miscellaneous Paper EL-86-6, US Army Engineer Waterways Experiment Station, Vicksburg, MS, pp B15-28, Monsanto Report No. ES-82-M-7.

Mosher, R. G., Kimerle, R. A., and Adams, W. J. 1982. "MIC Environmental Assessment Method for Conducting 14-day Partial Life Cycle Flow-Through and Static Sediment Exposure Toxicity Tests with the Midge *Chironomus tentans*. Proceedings of a Workshop on Bioassessment Methodologies for the Regulatory Testing of Freshwater Dredged Material, Miscellaneous Paper EL-86-6, US Army

Engineer Waterways Experiment Station, Vicksburg, MS, pp B29-B41, Monsanto Report No. ES-82-M-10.

Muir, D. C. G., Townsend, B. E., and Lockhart, W. L. 1983. "Bioavailability of Six Organic Chemicals to *Chironomus tentans* Larvae in Spiked Sediment and Water," Environmental Toxicology and Chemistry, Vol 2, pp 269-281.

Nebeker, A. V., and Miller, C. E. 1988. "Use of the Amphipod Crustacean *Hyalella azteca* in Freshwater and Estuarine Sediment Toxicity Tests," Environmental Toxicology and Chemistry, Vol 7, pp 1027-1033.

Nebeker, A. V., Cairns, M. A., Gakstatter, J. H., Malueg, K. W., Schuytema, G. S., and Krawczyk, D. F. 1984. "Biological Methods for Determining Toxicity of Contaminated Freshwater Sediments to Invertebrates," Environmental Toxicology and Chemistry, Vol 3, pp 617-630.

Nebeker, A. V., Onjukka, S. T., Cairns, M. A., and Krawczyk, D. F. 1986. "Survival of *Daphnia magna* and *Hyalella azteca* in Cadmium-Spiked Water and Sediment," Environmental Toxicology and Chemistry, Vol 5, pp 933-93.

Neff, J. M. 1984. "Bioaccumulation of Organic Micropollutants from Sediments and Suspended Particulates by Aquatic Animals," Fresenius Zeitschift Analytische Chemie, Vol 319, pp 132-136.

Nelson, M. K., Ingersoll, C. G., and Dwyer, F. J., "Proposed Guide for Conducting Solid-Phase Sediment Toxicity Tests with Freshwater Invertebrates," Technical Report (in preparation), US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Nyffeler, U. P., Li, Y. H., and Santschi, P. H. 1984. "A Kinetic Approach to Describe Trace-Element Distribution Between Particles and Solutions in Natural Aquatic Systems," Geochemica et Cosmochimica Acta, Vol 48, pp 1513-1522.

Oishi, S., and Takahashi, O. 1987. "Mutagenicity of Tama River Sediments," Bulletin of Environmental Contamination and Toxicology, Vol 39, pp 696-700.

Oliver, B. G. 1987. "Biouptake of Chlorinated Hydrocarbons from Laboratory-Spiked and Field Sediments by Oligochaete Worms," Environmental Science and Technology, Vol 21, pp 785-790.

Olsen, L. A. 1984. "Effects of Contaminated Sediment on Fish and Wildlife: Review and Annotated Bibliography," Report OBS-82/66, US Fish and Wildlife Service, Washington, DC.

Prater, B. L., and Anderson, M. A. 1977. "A 96-Hour Sediment Bioassay of Duluth and Superior Harbor Basins (Minnesota) Using *Hexagenia limbata, Asellus communis, Daphnia magna*, and *Pimephales promelas* as Test Organisms," Bulletin of Environmental Contamination and Toxicology, Vol 18, pp 159-169.

Samoiloff, M. R., Bell, J., Birkolz, D. A., Webster, G. R. B., Arnott, E. R., Pulak, R., and Madrid, A. 1983. "Combined Bioassay-Chemical Fractionation Scheme for the Determination and Ranking of Toxic Chemicals in Sediments," Environmental Science and Technology, Vol 17, pp 329-334.

Saucier, R. A., Calhoun, C. C., Jr., Engler, R. M., Patin, T. R., and Smith, H. K. 1978. "Executive Overview and Detailed Summary," Technical Report DS-78-22, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Schuytema, G. S., Krawczyk, D. F., Griffis, W. L., Nebeker, A. V., Robideaux, M. L., Brownawell, B. J., and Westall, J. C. 1988. "Comparative

Uptake of Hexachlorobenzene by Fathead Minnows, Amphipods and Oligochaete Worms from Water and Sediment," Environmental Toxicology and Chemistry, Vol 7, pp 1035-1045.

Seelye, J. G., and Mac, M. J. 1984. "Bioaccumulation of Toxic Substances Associated with Dredging and Dredged Material Disposal," Interagency Agreement AD-14-F-1-529-9, Great Lakes National Program Office, US Environmental Protection Agency, Chicago, IL.

Seelye, J. G., Hesselberg, R. J., and Mac, M. J., 1982. "Accumulation by Fish of Contaminants Released from Dredged Sediments," Environmental Sciences and Technology, Vol 16, pp 459-464.

Swindoll, C. M., and Applehans, F. M. 1987. "Factors Influencing the Accumulation of Sediment-Sorbed Hexachlorobiphenyl by Midge Larvae," Bulletin of Environmental Contamination and Toxicology, Vol 39, pp 1055-1062.

Tennant, R. W. 1987. "Issues in Biochemical Applications to Risk Assessment: Are Short-Term Tests Predictive of in vivo Tumorigenicity?," Environmental Health Perspectives, Vol 76, pp 163-167.

Tessier, A., Campbell, P. G. C., Auclair, J. C., and Bisson, M. 1984. "Relationships Between the Partitioning of Trace Metals in Sediments and Their Accumulation in the Tissues of the Freshwater Mollusc (*Elliptio complanata*) in a Mining Area," Canadian Journal of Fishing and Aquatic Science, Vol 41, pp 1463-1472.

Ward, S. "Acute and Chronic Toxicity of Sediments to Aquatic Organisms" (in preparation), Hunter/ESE Report for US Army Engineer District, St. Paul.

Wentsel, R., McIntosh, A., and Atchison, G. 1977. "Sublethal Effects of Heavy-Metal-Contaminated Sediment on Midge Larvae (*Chironomus tentans*)," Hydrobiologia, Vol 56, pp 153-156.

Wentsel, R., McIntosh, A., and McCafferty, W. P. 1978. "Emergence of the Midge (*Chironomus tentans*) When Exposed to Heavy-Metal-Contaminated Sediment," Hydrobiologia, Vol 57, pp 195-196.

Wentsel, R., McIntosh, A., McCafferty, W. P., Atchison, G., and Anderson, V. 1977. "Avoidance Response of Midge Larvae (*Chironomous tentans*) to Sediments Containing Heavy Metals," Hydrobiologia, Vol 55, pp 171-175.

West, W. R., Smith, P. A., Booth, G. M., and Lee, M. L. 1986. "Determination and Genotoxicity of Nitrogen Heterocycles in a Sediment from the Black River," Environmental Toxicology and Chemistry, Vol 5, pp 511-519.

West, W. R., Smith, P. A., Booth, G. M., and Lee, M. L. 1988. "Isolation and Detection of Genotoxic Components in a Black River Sediment," Environmental Science and Technology, Vol 22, pp 224-228.

White, D. S., and Keilty, T. J. 1988. "Burrowing Avoidance Assays of Contaminated Detroit River Sediments, Using the Freshwater Oligochaete (*Stylodrilus heringianus*) (lumbriculidae)," Archives of Environmental Contamination and Toxicology, Vol 17, pp 673-681.

Wood, L. W., Rhee, G. Y., Bush, B., and Barnard, E. 1987. "Sediment Desorption of PCB Congeners and Their Bio-uptake by Dipteran Larvae," Water Resources, Vol 21, pp 875-884.

Ziegenfuss, P. S., and Adams, W. J. 1985. "A Method for Assessing the Acute Toxicity of Contaminated Sediments and Soils with *Daphnia magna* and *Chironomus tentans*," Proceedings of a Workshop on Bioassessment Methodologies for the Regulatory Testing of Freshwater Dredged Material, Miscellaneous Paper EL-86-6, US Army Engineer Waterways Experiment Station, Vicksburg, MS, pp B3-B14, Monsanto Report No. ESC-EAG-M-85-01.

APPENDIX A: BIBLIOGRAPHY OF CONTAMINANT-SPECIFIC FRESHWATER SEDIMENT BIOASSESSMENT TECHNIQUES

Boddington, M. J., DeFreitas, A. S. W., and Miller, D. R. 1979. "The Effect of Benthic Invertebrates on the Clearance of Mercury from Sediments," Ecotoxicology and Environmental Safety, Vol 3, pp 236-244.

Burton, G. A., Jr., Lazorchak, J. M., Waller, W. T., and Lanza, G. R. 1987. "Arsenic Toxicity Changes in the Presence of Sediment," Bulletin of Environmental Contamination and Toxicology, Vol 38, pp 491-499.

Cairns, M. A., Nebeker, A. V., Gakstatter, J. H., and Griffis, W. L. 1984. "Toxicity of Copper-Spiked Sediments to Freshwater Invertebrates," Environmental Toxicology and Chemistry, Vol 3, pp 435-445.

Diks, D. M., and Allen, H. E. 1983. "Correlation of Copper Distribution in a Freshwater-Sediment System to Bioavailability," Bulletin of Environmental Contamination and Toxicology, Vol 30, pp 37-43.

Feijtel, T. C., Delaune, R. D., and Patrick, W. H., Jr. 1988. "Biogeochemical Control on Metal Distribution and Accumulation in Louisiana Sediments," Journal of Environmental Quality, Vol 17, pp 88-94.

Finley, K. A. 1985. "Observations of Bluegills Fed Selenium-Contaminated *Hexagenia* Nymphs Collected from Belews Lake, North Carolina," Bulletin of Environmental Contamination and Toxicology, Vol 35, pp 816-825.

Gillespie, D. C., and Scott, D. P. 1971. "Mobilization of Mercuric Sulfide from Sediment into Fish Under Aerobic Conditions," Journal of the Fishery Resources Board of Canada, Vol 28, pp 1807-1808.

Graney, R. L., Jr., Cherry, D. S., and Cairns, J., Jr. 1984. "The Influence of Substrate, pH, Diet, and Temperature upon Cadmium Accumulation in the Asiatic Clam (*Corbicula fluminea*) in Laboratory Artificial Streams," Water Resources, Vol 18, pp 833-842.

Hammer, U. T., Merkowsky, A. T., and Huang, P. M. 1988. "Effects of Oxygen Concentrations on Release of Mercury from Sediments and Accumulation by *Ceratophyllum demersum* and *Anodonta grandis*," Archives of Environmental Contamination and Toxicology, Vol 17, pp 257-262.

Kraft, K. J. 1979. "*Pontoporeia* Distribution Along the Keweenaw Shore of Lake Superior Affected by Copper Tailings," Journal of Great Lakes Resources, Vol 5, pp 28-35.

Kudo, A. 1976. "Mercury Transfer from Bed Sediments to Freshwater Fish (Guppies)," Journal of Environmental Quality, Vol 5, pp 427-430.

Kudo, A., Akagi, H., Mortimer, D. C., and Miller, D. R. 1977. "Equilibrium Concentrations of Methylmercury in Ottawa River Sediments," Nature, Vol 270, pp 419-420.

Kudo, A., Miller, D. R., Akagi, H., Mortimer, D. C., DeFreitas, A. S., Nagase, H., Townsend, D. R., and Warnock, R. G. 1978. "The Role of Sediments on Mercury Transport (Total-and Methyl-) in a River System," Progressive Water Technology, Vol 10, pp 329-339.

Lewis, T. E., and McIntosh, A. W. 1986. "Uptake of Sediment-Bound Lead and Zinc by the Freshwater Isopod (*Asellus communis*) at Three Different pH

Levels," Archives of Environmental Contamination and Toxicology, Vol 15, pp 495-504.

Malueg, K. W., Schuytema, G. S., Gakstatter, J. H., and Krawczyk, D. F. 1984. "Toxicity of Sediments from Three Metal-Contaminated Areas," Environmental Toxicology and Chemistry, Vol 3, pp 279-291.

Moriarty, F., Hanson, H. M., and Freestone, P. 1984. "Limitations of Body Burden as an Index of Environmental Contamination: Heavy Metals in Fish (*Cottus gobio* L.) from the River Ecclesbourne, Derbyshire," Environmental Pollution, Vol 34, pp 297-320.

Nebeker, A. V., Onjukka, S. T., Cairns, M. A., and Krawczyk, D. F. 1986. "Survival of *Daphnia magna* and *Hyalella azteca* in Cadmium-Spiked Water and Sediment," Environmental Toxicology and Chemistry, Vol 5, pp 933-993.

Rudd, J. W. M., and Turner, M. A. 1983. "The English-Wabigoon River System: II. Suppression of Mercury and Selenium Bioaccumulation by Suspended and Bottom Sediments," Canadian Journal of Fisheries and Aquatic Science, Vol 40, pp 2218-2227.

Schuytema, G. S., Nelson, P. O., Malueg, K. W., Nebeker, A. V., Krawczyk, D. F., Ratcliff, A. K., and Gakstatter, J. H. 1984. "Toxicity of Cadmium in Water and Sediment Slurries to *Daphnia magna*," Environmental Toxicology and Chemistry, Vol 3, pp 293-308.

Sherman, R. E., Gloss, S. P., and Lion, L. W. 1987. "A Comparison of Toxicity Tests Conducted in the Laboratory and in Experimental Ponds Using Cadmium and the Fathead Minnow (*Pimephales promelas*)," Water Resources, Vol 21, pp 317-323.

Smith, A. L., Green, R. H., and Lutz, A. 1975. "Uptake of Mercury by Freshwater Clams (Family Unionidae)," Journal of the Fishery Research Board of Canada, Vol 32, pp 1297-1303.

Tatem, H. W. 1986. "Bioaccumulation of Polychlorinated Biphenyls and Metals from Contaminated Sediment by Freshwater Prawns (*Macrobrachium rosenbergii*) and Clams (*Corbicula fluminea*)," Archives of Environmental Contamination and Toxicology, Vol 15, pp 171-183.

Tessier, A., Campbell, P. G. C., Auclair, J. C., and Bisson, M. 1984. "Relationships Between the Partitioning of Trace Metals in Sediments and Their Accumulation in the Tissues of the Freshwater Mollusc (*Elliptio complanata*) in a Mining Area," Canadian Journal of Fishing and Aquatic Sciences, Vol 41, pp 1463-1472.

Warren, L. J. 1981. "Contamination of Sediments by Lead, Zinc, and Cadmium: A Review," Environmental Pollution, Vol 2, pp 401-436.

Wentsel, R., McIntosh, A., and Atchison, G. 1977. "Sublethal Effects of Heavy-Metal-Contaminated Sediment on Midge Larvae (*Chironomus tentans*)," Hydrobiologia, Vol 56, pp 153-156.

Wentsel, R., McIntosh, A., McCafferty, W. P., Atchison, G., and Anderson, V. 1977. "Avoidance Response of Midge Larvae (*Chironomus tentans*) to Sediments Containing Heavy Metals," Hydrobiologia, Vol 55, pp 171-175.

Wentsel, R., McIntosh, A., and McCafferty, W. P. 1978. "Emergence of the Midge (*Chironomus tentans*) when Exposed to Heavy-Metal-Contaminated Sediment," Hydrobiologia, Vol 57, pp 195-196.

Wren, C. D., and MacCrimmon, H. R. 1986. "Comparative Bioaccumulation of Mercury in Two Adjacent Freshwater Ecosystems," Water Resources, Vol 20, pp 763-769.

Zauke, G. P. 1981. "Cadmium in Gammaridae (Amphipoda: Crustacea) of the Rivers Werra and Weser: Geographical Variation and Correlation to Cadmium in Sediments," Environmental Pollution, Vol 2, pp 465-474.

CHLORINATED COMPOUNDS

Adams, W. J., Kimerle, R. A., and Mosher, R. G. 1985. "Aquatic Safety Assessment of Chemicals Sorbed to Sediments," Seventh Symposium on Aquatic Toxicology and Hazard Assessment, ASTM STP 854, R. D. Cardwell, R. Purdy, and R. C. Bahner, eds., American Society for Testing and Materials, Philadelphia, PA, pp 429-453.

Adams, W. J., Ziegenfuss, P. S., Renaudette, W. J., and Mosher, R. G. 1986. "Comparison of Laboratory and Field Methods for Testing the Toxicity of Chemicals Sorbed to Sediments," Aquatic Toxicology and Environmental Fate, Vol 9, ASTM STP 921, T. M. Poston and R. Purdy, eds., American Society for Testing and Materials, Philadelphia, PA, pp 493-513.

Biddinger, G. R., and Gloss, S. P. 1984. "The Importance of Trophic Transfer in the Bioaccumulation of Chemical Contaminants in Aquatic Ecosystems," Residues Review, Vol 91, pp 104-130.

Bridgham, S. D. 1988. "Chronic Effects of 2,2'-Dichlorobiphenyl on Reproduction, Mortality, Growth, and Respiration of *Daphnia pulicaria*," Archives of Environmental Contamination and Toxicology, Vol 17, pp 731-740.

Brown, J. F., Jr., Bedard, D. L., Brennan, M. J., Carnaha, J. C., Feng, H., and Wagner, R. E. 1987. "Environmental Dechlorination of PCB's," Environmental Toxicology and Chemistry, Vol 6, pp 579-593.

Brown, M. P., Werner, M. B., Sloan, R. J., and Simpson, K. W. 1985. "Polychlorinated Biphenyls in the Hudson River," Environmental Science and Technology, Vol 19, pp 656-660.

Broyles, R. H., and Noveck, M. I. 1979. "Uptake and Distribution of 2,4,5,2', 4',5'-Hexachlorobiphenyl in Fry of Lake Trout and Chinook Salmon and its Effects on Viability," Toxicology and Applied Pharmacology, Vol 50, pp 299-308.

Burris, D. E., and Huggett, R. J. 1984. "Evaluation of Elutriate Test Parameters for an Organic Hydrophobic Pollutant, Kepone," Environmental Pollution, Vol 8, pp 63-69.

Califano, R. J., O'Connor, J. M., and Hernandez, J. A. 1982. "Polychlorinated Biphenyl Dynamics in Hudson River Striped Bass, Vol I. Accumulation in Early Life History Stages," Aquatic Toxicology, Vol 2, pp 187-204.

Dillon, T. M. 1988. "Relationship Between PCB Tissue Residues and Reproductive Success of Fathead Minnows," Technical Note EEDP-01-13, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Elder, J. F., and Mattraw, H. C., Jr. 1984. "Accumulation of Trace Elements, Pesticides, and Polychlorinated Biphenyls in Sediments and the Clam

(*Corbicula manilensis*) of the Apalachicola River, Florida," Archives of Environmental Contamination and Toxicology, Vol 13, pp 453-469.

Eisenreich, S. J., Hollod, G. J., Johnson, T. C., and Evans, J. 1980. "Polychlorinated Biphenyl and other Microcontaminant-Sediment Interactions in Lake Superior," Contaminants and Sediments, Vol 1, Robert A. Baker, ed., Ann Arbor Science Publishers, Inc., Ann Arbor, MI, pp 67-94.

Fisher, J. B., Petty, R. L., and Lick, W. 1983. "Release of Polychlorinated Biphenyls from Contaminated Lake Sediments: Flux and Apparent Diffusivities of Four Individual PCB's," Environmental Pollution, Vol 5, pp 121-132.

Hartley, D. M., and Johnston, J. B. 1983. "Use of the Freshwater Clam (*Corbicula manilensis*) as a Monitor for Organochlorine Pesticides," Bulletin of Environmental Contamination and Toxicology, Vol 31, pp 33-40.

Kay, S. H. 1984. "Potential for Biomagnification of Contaminants Within Marine and Freshwater Food Webs," Technical Report D-84-7, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Keilty, T. J., White, D. S., and Landrum, P. F. 1988. "Short-term Lethality and Sediment Avoidance Assays with Endrin-Contaminated Sediment and Two Oligochaetes from Lake Michigan," Archives of Environmental Contamination and Toxicology, Vol 17, pp 95-101.

Knezovich, J. P., and Harrison, F. L. 1988. "The Bioavailability of Sediment-Sorbed Chlorobenzenes to Larvae of the Midge, *Chironomus decorus*," Ectoxicology and Environmental Safety, Vol 15, pp 226-241.

Larsson, P. 1986. "Zooplankton and Fish Accumulate Chlorinated Hydrocarbons from Contaminated Sediments," Canadian Journal of Fisheries and Aquatic Science, Vol 43, pp 1463-1466.

McFarland, V., and Clarke, J. 1987. "Simplified Approach for Evaluating Bioavailability of Neutral Organic Chemicals in Sediment," Environmental Effects of Dredging Technical Notes EEDP-01-8, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Muir, D. C. G., Townsend, B. E., and Lockhart, W. L. 1983. "Bioavailability of Six Organic Chemicals to *Chironomus tentans* Larvae in Spiked Sediment and Water," Environmental Toxicology and Chemistry, Vol 2, pp 269-281.

Muir, D. C. G., Grift, N. P., Townsend, B. E., Metner, D. A., and Lockhart, W. L. 1982. "Comparison of the Uptake and Bioconcentration of Fluriodone and Terbutryn by Rainbow Trout and *Chironomus tentans* in Sediment and Water Systems," Archives of Environmental Contamination and Toxicology, Vol 11, pp 595-602.

O'Keefe, P. W., Hilker, D. R., Smith, R. M., Aldous, K. M., Donnelly, R. J., Long, D., and Pope, D. H. 1986. "Nonaccumulation of Chlorinated Dioxins and Furans by Goldfish Exposed to Contaminated Sediment and Flyash," Bulletin of Environmental Contamination and Toxicology, Vol 36, pp 452-459.

Oliver, B. G. 1987. Bio-uptake of Chlorinated Hydrocarbons from Laboratory-Spiked and Field Sediments by Oligochaete Worms," Environmental Science and Technology, Vol 21, pp 785-790.

Peterson, R. E., and Guiney, P. D. 1979. "Disposition of Polychlorinated Biphenyls in Fish," Pesticide and Xenobiotic Metabolism in Aquatic Organisms, Proceedings of the 176th Meeting of the American Chemical Society, September 11-17, 1978, Miami Beach, FL, pp 21-36.

Rice, C. P., and White D. S. 1987. "PCB Availability Assessment of River Dredging Using Caged Clams and Fish," Environmental Toxicology and Chemistry, Vol 6, pp 259-274.

Sanborn, J. R., Childers, W. F., and Metcalf, R. L. 1975. "Uptake of Three Polychlorinated Biphenyls, DDT, and DDE by the Green Sunfish *(Lepomis cyanellus* Raf.)," Bulletin of Environmental Contamination and Toxicology, Vol 13, pp 209-217.

Schober, U., and Lampert, W. 1977. "Effects of Sublethal Concentrations of the Herbicide Atrazine on Growth and Reproduction of *Daphnia pulex*," Bulletin of Environmental Contamination and Toxicology, Vol 17, pp 269-277.

Schuytema, G. S., Krawczyk, D. F., Griffis, W. L., Nebeker, A. V., Robideaux, M. L., Brownawell, B. J., and Westall, J. C. 1988. "Comparative Uptake of Hexachlorobenzene by Fathead Minnows, Amphipods, and Oligochaete Worms from Water and Sediment," Environmental Toxicology and Chemistry, Vol 7, pp 1035-1045.

Sullivan, J. R., Delfino, J. J., Buelow, C. R., and Sheffy, T. B. 1983. "Polychlorinated Biphenyls in the Fish and Sediment of the Lower Fox River, Wisconsin," Bulletin of Environmental Contamination and Toxicology, Vol 30, pp 58-64.

Swindoll, C. M. and Applehans, F. M. 1987. "Factors Influencing the Accumulation of Sediment-Sorbed Hexachlorobiphenyl by Midge Larva," Bulletin of Environmental Contamination and Toxicology, Vol 39, pp 1055-1062.

Tatem, H. E. 1986. "Bioaccumulation of Polychlorinated Biphenyls and Metals from Contaminated Sediments by Freshwater Prawns (*Macrobrachium rosenbergii*) and Clams (*Corbicula Fluminea*)," Archives of Environmental Contamination and Toxicology, Vol 15, pp 171-183.

Van der Oost, R., Heida, H., and Opperhuizen, A. 1988. "Polychlorinated Biphenyl Congeners in Sediments, Plankton, Molluscs, Crustaceans, and Eel in a Freshwater Lake: Implications of Using Reference Chemicals and Indicator Organisms in Bioaccumulation Studies," Archives of Environmental Contamination and Toxicology, Vol 17, pp 721-729.

Wood, L. W., Rhee, G.-Y., Bush, B., and Barnard, E. 1987. "Sediment Desorption of PCB Congeners and their Bio-uptake by Dipteran Larvae," Water Resources, Vol 21, pp 875-884.

Ziegenfuss, P. S., Renaudette, W. J., and Adams, W. J. 1986. "Methodology for Assessing the Acute Toxicity of Chemicals Sorbed to Sediments: Testing the Equilibrium Partitioning Theory," Aquatic Toxicology and Environmental Fate, Vol 9, ASTM STP 921, T. M. Poston and R. Purdy, eds., American Society for Testing and Materials, Philadelphia, PA, pp 479-493.

POLYCYCLIC AROMATIC HYDROCARBONS (PAH's)

Catallo, W. J., III, and Gambrell, R. P. 1987. "The Effects of High Levels of Polycyclic Aromatic Hydrocarbons on Sediment Physicochemical Properties and Benthic Organisms in a Polluted Stream," Chemosphere, Vol 16, pp 1053-1063.

Eadie, B. J., Faust, W. R., Landrum, P. F., Morehead, N. R., Gardner, W. S., and Nalepa, T. 1982. "Bioconcentrations of PAH by Some Benthic Organisms of the Great Lakes," Polynuclear Aromatic Hydrocarbons, Seventh International Symposium on Formation, Metabolism and Measurement, M. W. Cooke and A. J. Dennis, eds., Battelle Press, Columbus, OH.

Eadie, B. J., Landrum, P. F., and Faust, W. 1982. "Polycyclic Aromatic Hydrocarbons in Sediments, Pore Water, and the Amphipod (*Pontoporeia hoyi*) from Lake Michigan," Chemosphere, Vol 11, pp 847-858.

Fabacher, D. L., Schmitt, C. J., Besser, J. M., and Mac, M. J. 1988. "Chemical Characterization and Mutagenic Properties of Polycyclic Aromatic Compounds in Sediment from Tributaries of the Great Lakes," Environmental Toxicology and Chemistry, Vol 7, pp 529-543.

Frank, A. P., Landrum, P. F., and Eadie, B. J. 1986. "Polycyclic Aromatic Hydrocarbon Rates of Uptake, Depuration, and Biotransformation by Lake Michigan *Stylodrilus heringianus*," Chemosphere, Vol 15, pp 317-330.

Landrum, P. F. 1982. "The Effect of Co-contaminants of the Bioavailability of Polycyclic Aromatic Hydrocarbons to (*Pontoporeia hoyi*)," Poly-nuclear Aromatic Hydrocarbons, Seventh International Symposium on Formation, Metabolism and Measurement, M. W. Cooke and A. J. Dennis, eds., Battelle Press, Columbus, OH.

Landrum, P. F. 1982. "Uptake, Depuration and Biotransformation of Anthracene by the Scud (*Pontoporeia hoyi*)," Chemosphere, Vol 11, pp 1049-1057.

Landrum, P. F. 1988. "Toxicokinetics of Organic Xenobiotics in the Amphipod, (*Pontoporeia hoyi*): Role of Physiological and Environmental Variables," Aquatic Toxicology, Vol. 12, pp 245-271.

Landrum, P. F., and Poore, R. 1988. "Toxicokinetics of Selected Xenobiotics in *Hexagenia limbata*," Journal of Great Lakes Resources, Vol 14, pp 427-437.

Landrum, P. F., and Scavia, D. 1983. "Influence of Sediment on Anthracene Uptake, Depuration, and Biotransformation by the Amphipod (*Hyalella azteca*)," Canadian Journal of Fisheries and Aquatic Science, Vol 40, pp 298-305.

Landrum, P. F., Eadie, B. J., Faust, W. R., Morehead, N. R., and McCormick, M. J. 1983. "Role of Sediment on the Bioaccumulation of Benzo(a)pyrene by the Amphipod (*Pontoporeia hoyi*)," Polynuclear Aromatic Hydrocarbons, Eighth International Symposium on Mechanisms, Methods and Metabolism, M. W. Cooke and A. J. Dennis, eds., Battelle Press, Columbus, OH.

Landrum, P. F., Reinhold, M. D., Nihart, S. R., and Eadie, B. J. 1985. "Predicting the Bioavailability of Organic Xenobiotics to *Pontoporeia hoyi* in the Presence of Humic and Fulvic Materials and Natural Dissolved Organic Matter," Environmental Toxicology and Chemistry, Vol 4, pp 459-467.

Landrum, P. F., Nihart, S. R., Eadie, B. J., and Herche, L. R. 1987. "Reduction in Bioavailability of Organic Contaminants to the Amphipod *Pontoporeia* *hoyi* by Dissolved Organic Matter of Sediment Interstitial Waters," Environmental Toxicology and Chemistry, Vol 6, pp 11-20.

McElroy, A. E., Tripp, B. W., Farrington, J. W., and Teal, J. M. 1987. "Biogeochemistry of Benz(a)anthracene at the Sediment-Water Interface," Chemosphere, Vol 16, pp 2429-2440.

West, W. R., Smith, P. A., Booth, G. M., Weis, S. A., and Lee, M. L. 1986. "Determination of Genotoxic Polycyclic Aromatic Hydrocarbons in a Sediment from the Black River (Ohio)," Archives of Environmental Contamination and Toxicology, Vol 15, pp 241-249.